Low Mass Dark Matter and Invisible Higgs Width In Darkon Models

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Phys. Rev. D 83 083524, 2011 [arXiv:1102.1522]

理论物理国家重点实验室 SKLTP

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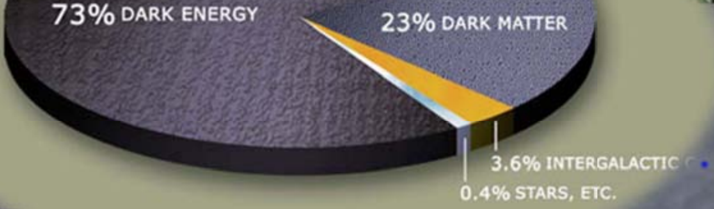
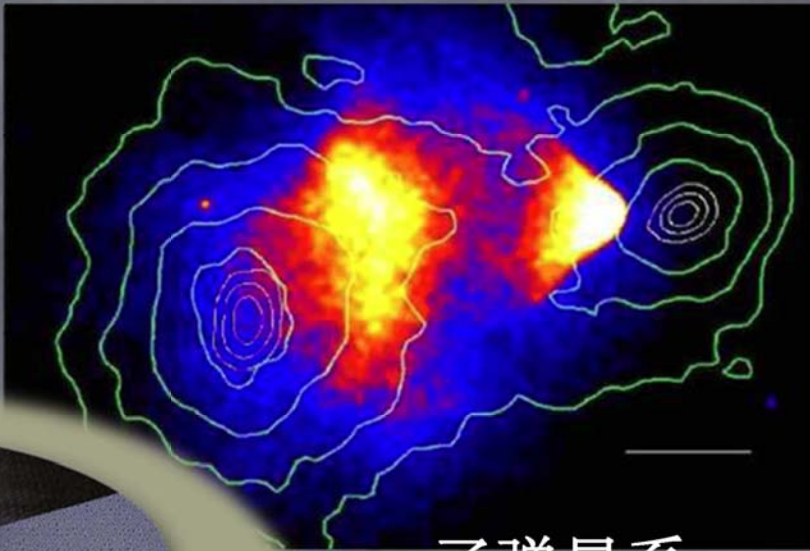
2. Two-Higgs-Doublet Model With A Darkon

3. Discussions and Conclusions

Evidences of DM from gravitational effects Gravitational

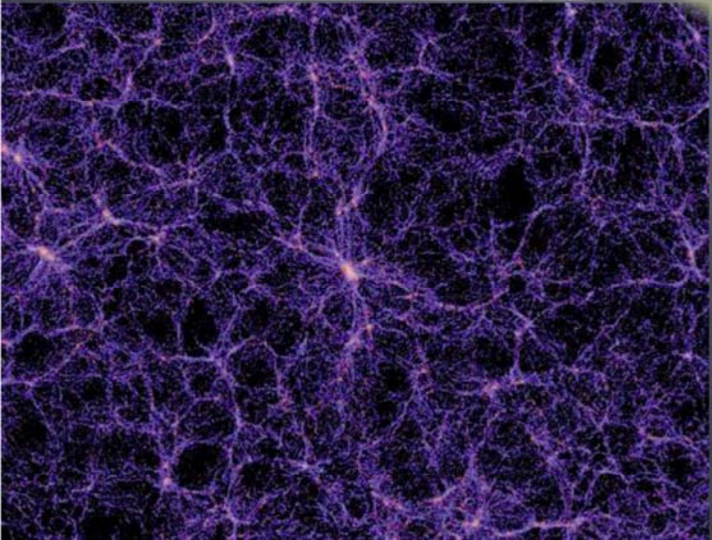
引力透镜



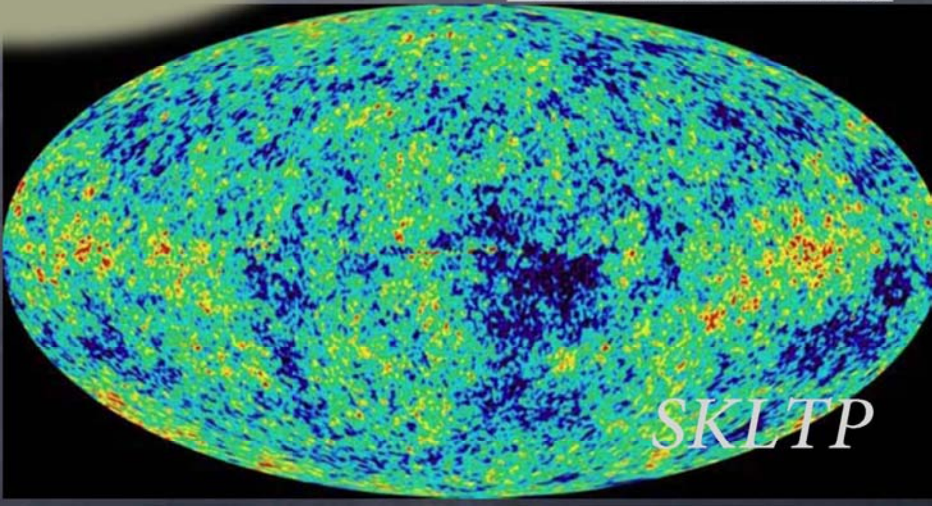


子弹星系

宇宙的大尺度结构



宇宙背景辐射

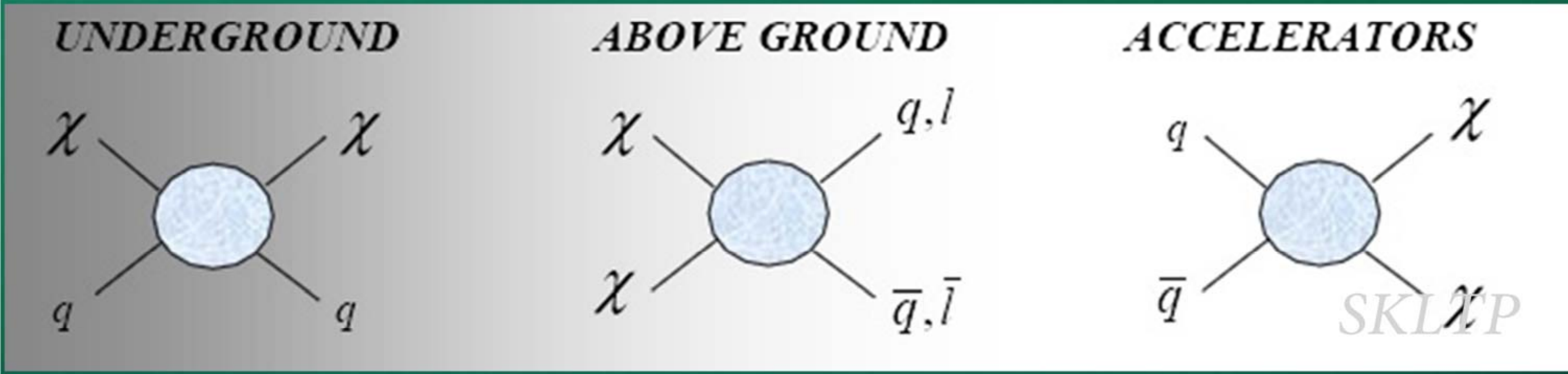


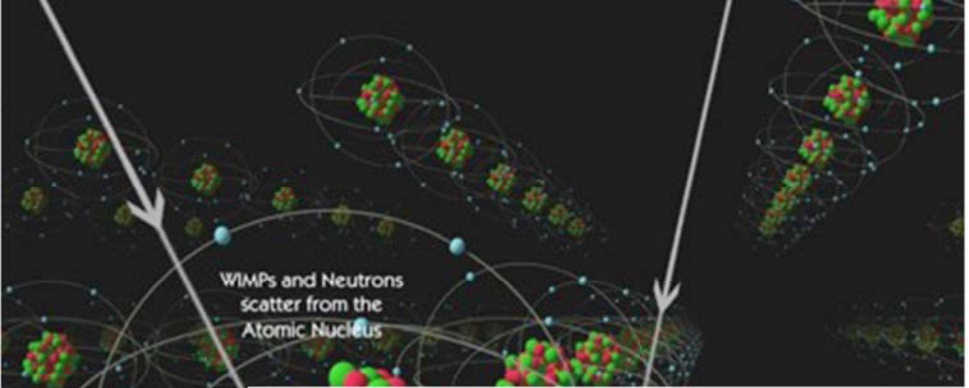
What is dark matter and how to detect it?

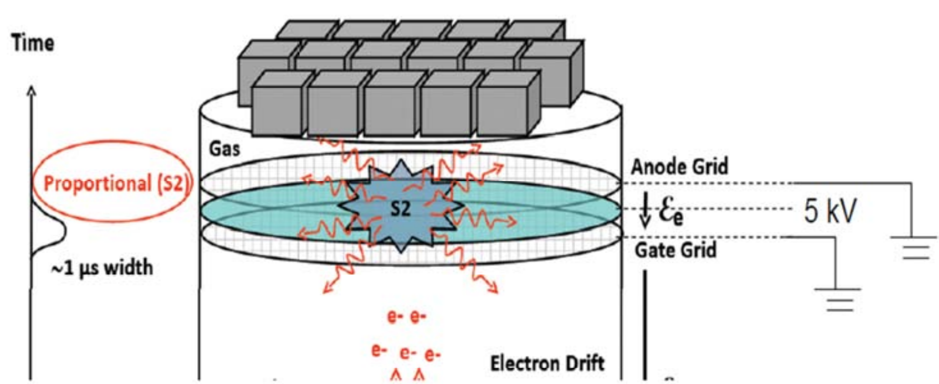
Weakly **I**nteractive **M**assive **P**article (**WIMP**)

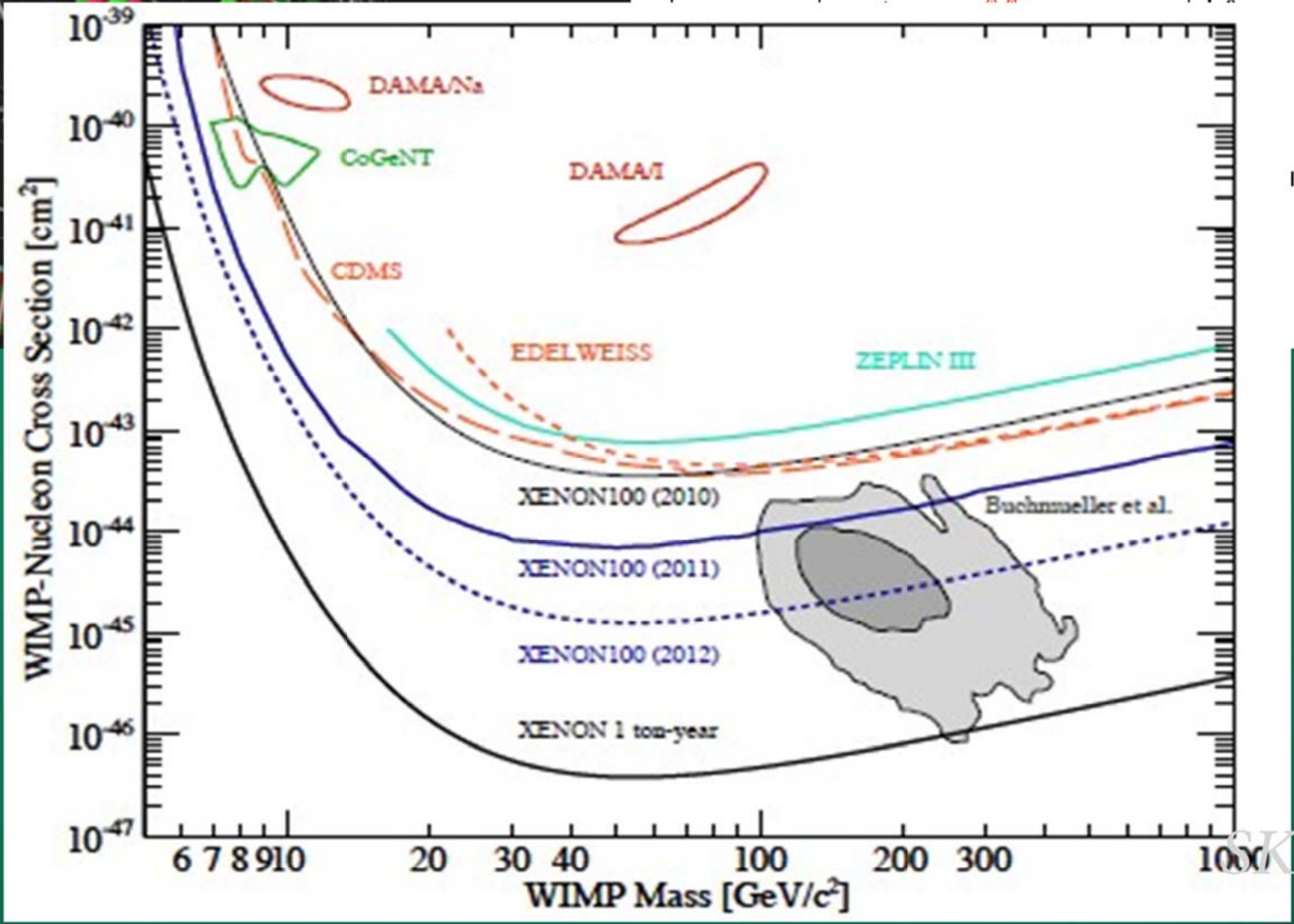
- stable
- slow
- relic from the Big Bang

Heavy, no charge, not in Standard Model




WIMPs and Neutrons
scatter from the
Atomic Nucleus


Time
Proportional (S2)
~1 μs width
Gas
S2
Anode Grid
$\mathcal{E}_e$
5 kV
Gate Grid
e- e-
e- e- e-
Electron Drift
-10 kV


WIMP-Nucleon Cross Section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
ZEPLIN III
XENON100 (2010)
Buchmueller et al.
XENON100 (2011)
XENON100 (2012)
XENON 1 ton-year
6 7 8 9 10
20
30 40
100
200 300
1000
WIMP Mass [GeV/c^2]

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1. The Simplest Dark Matter Model

The simplest dark model is the darkon model:
SM + real singlet D.
Renormalizable interaction only with SM Higgs is

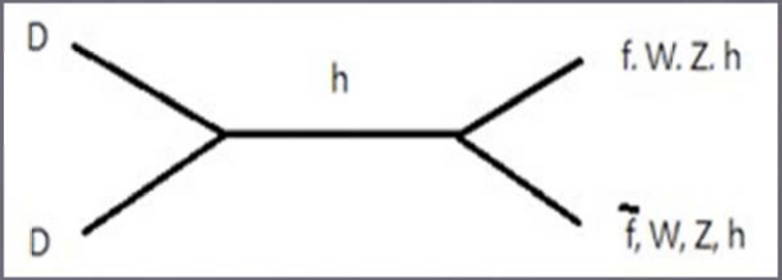
$$L_D = -\frac{\lambda_D}{4} D^4 - \frac{m_0^2}{2} D^2 - \lambda D^2 H^+ H$$

with the Z_2 symmetry, D -> -D. If not broken,
D can play the role of stable dark matter.

$$L_D = -\frac{\lambda_D}{4} D^4 - \frac{(m_0^2 + \lambda \upsilon^2)}{2} D^2 - \frac{\lambda}{2} D^2 h^2 - \lambda \upsilon D^2 h$$

where $\upsilon = 246\ \mathrm{GeV}$ vacuum expectation value of H,
darkon mass $m_D = (m_0^2 + \lambda \upsilon^2)^{1/2}$.

D is stable, but can annihilate through h exchange, namely $DD \to h^* \to X$, where X indicates SM particles



$$\sigma_{ann} \upsilon_{rel} = \frac{8\lambda^2 \upsilon^2}{(4m_D^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \frac{\sum_i \Gamma(\tilde{h} \to X_i)}{2m_D}$$

where $\upsilon_{rel} = 2|p_D^{cm}|/m_D$ is the relative speed of the DD pair in their cm frame, $\tilde{h}$ is a virtual Higgs boson with an invariant mass $\sqrt{s} = 2m_D$ which couples to the other states as the physical h with mass m_h, and $\tilde{h} \to X_i$ is any possible decay mode of $\tilde{h}$. For a given model, $\sum_i \Gamma(\tilde{h} \to X_i)$ is obtained by calculating the decay width of h and replacing m_h with $2m_D$.

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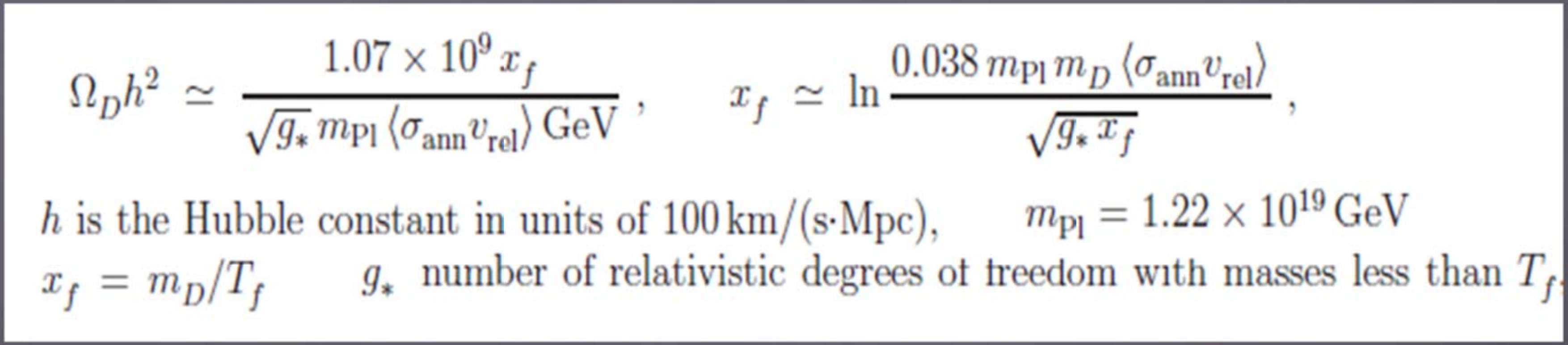
For a given interaction of the WIMP with SM particles, its annihilation rate into the latter and its relic density Ω_D can be calculated and are related to each other by the thermal dynamics of the Universe within the standard big-bang cosmology.

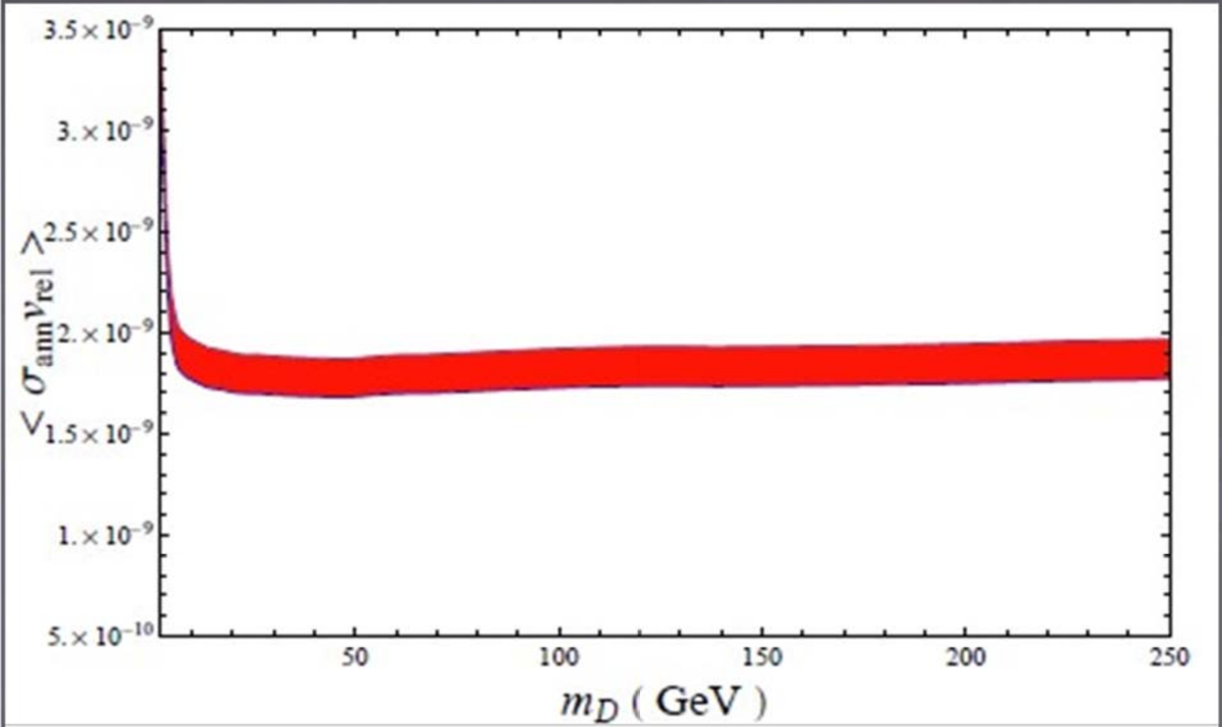


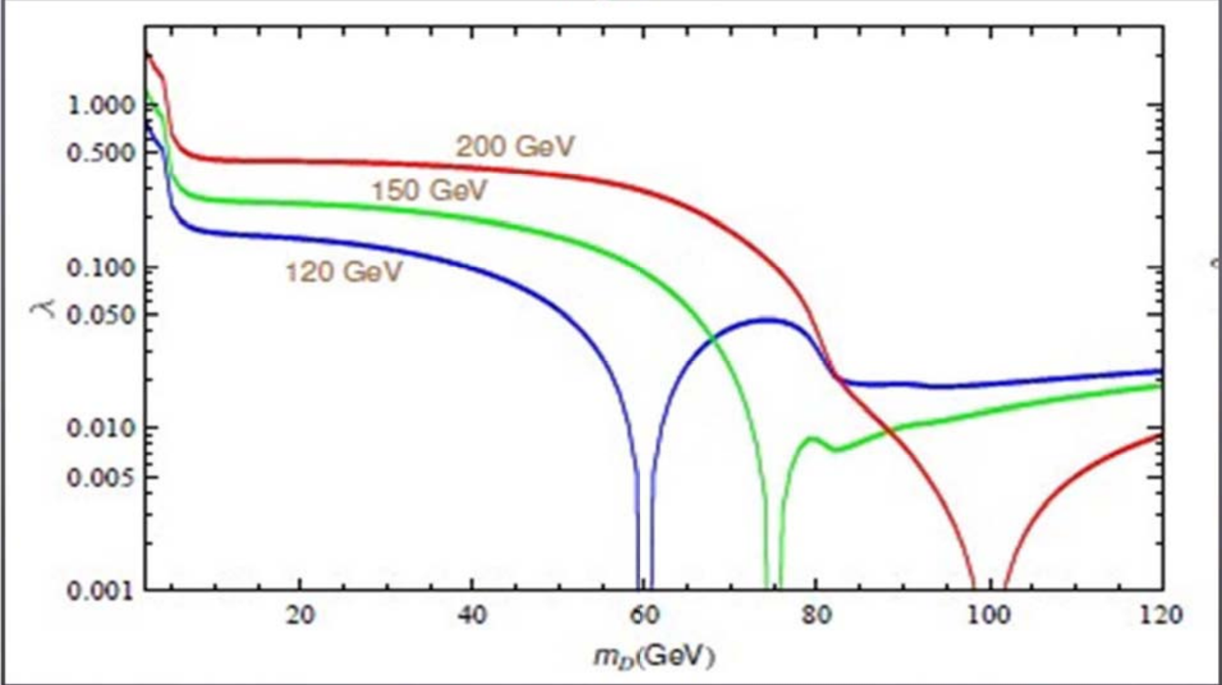
$$\Omega_D h^2 \simeq \frac{1.07 \times 10^9 \, x_f}{\sqrt{g_*}\, m_{\rm Pl} \langle \sigma_{\rm ann} v_{\rm rel} \rangle \, {\rm GeV}}, \qquad x_f \simeq \ln \frac{0.038\, m_{\rm Pl}\, m_D \langle \sigma_{\rm ann} v_{\rm rel} \rangle}{\sqrt{g_* x_f}},$$

h is the Hubble constant in units of 100 km/(s·Mpc), $m_{\rm Pl} = 1.22 \times 10^{19}\,{\rm GeV}$

$x_f = m_D/T_f$ g_* number of relativistic degrees of freedom with masses less than T_f

We can restrict the ranges of x_f and $\langle \sigma_{ann} v_{rel} \rangle$ as functions of WIMP mass m_D without knowing the explicit form of the SM-WIMP interaction.





The band width

$$0.1065 \leq \Omega_D h^2 \leq 0.1181$$

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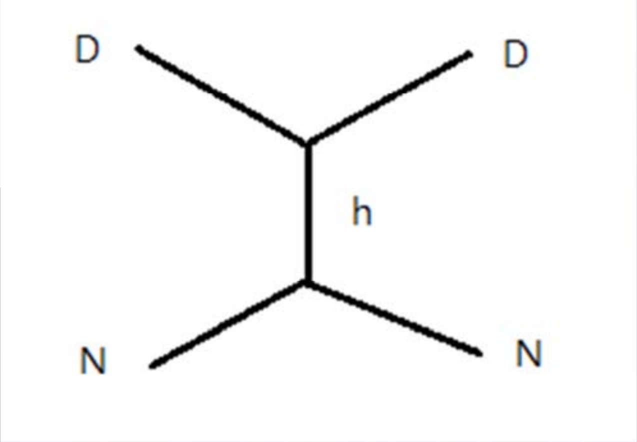
The elastic cross section of DM with nucleon and direct DM search data



$$\sigma_{el} \simeq \frac{\lambda^2 g_{NNh}^2 \upsilon^2 m_N^2}{\pi (m_D + m_N)^2 m_h^4}$$

The coupling of a Higgs boson H to quarks can be written as

$$L_{qqH} = -\sum_q \frac{k_q}{\upsilon} m_q \bar{q} q H$$

where the sum over the six quark flavor. In the SM $k_q = 1$ for all q's.

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Now, the effective coupling of H to a nucleon N=p or n has the form

$$L_{NNH} = -g_{NNH}\bar{N}NH$$

where g_{NNH} is the Higgs-nucleon coupling constant. By evaluating the matrix element

$$g_{NNH}\bar{N}N = \langle N|\frac{k_u}{v}(m_u\bar{u}u + m_c\bar{c}c + m_t\bar{t}t) + \frac{k_d}{v}(m_d\bar{d}d + m_s\bar{s}s + m_b\bar{b}b)|N\rangle$$

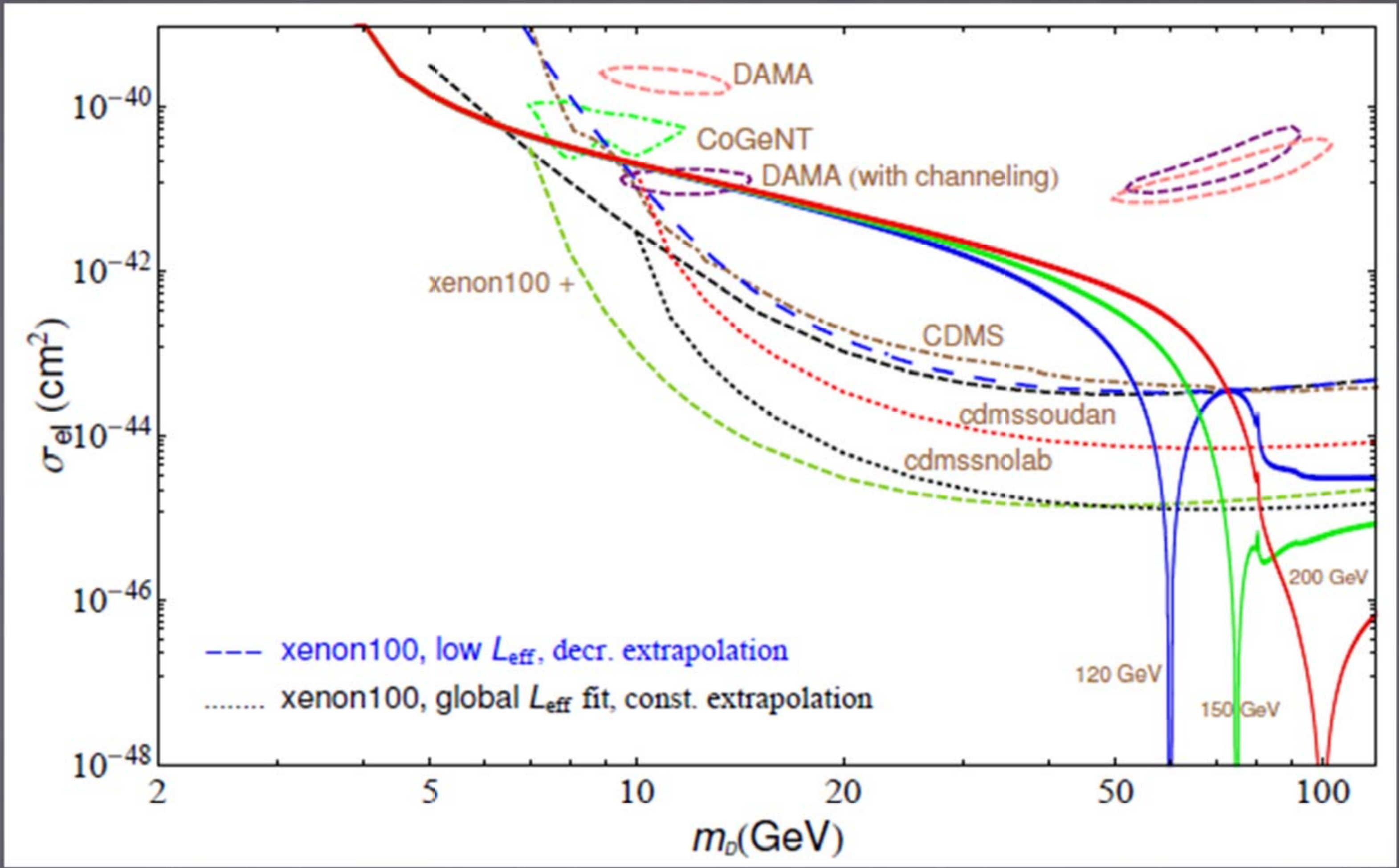
The result is

$$g_{NN\mathcal{H}} = (k_u - k_d)\frac{\sigma_{\pi N}}{2v} + k_d\frac{m_N}{v} + \frac{4k_u - 25k_d}{27}\frac{m_B}{v}$$

where $\sigma_{\pi N}$ is the so-called pion-nucleon sigma term, the m_N nucleon mass, and m_B the baryon mass in the chiral limit.

$$\sigma_{\pi N} \quad 35\,\mathrm{MeV} \text{ to } 80\,\mathrm{MeV} \quad 1.3\times10^{-3} \lesssim g^{\mathrm{SM3}}_{NNh} \lesssim 3.2\times10^{-3}.$$

$$g^{SM}_{NNh} \simeq 1.71\times10^{-3}$$



Darkon Nucleon elastic cross section σ_{el} as function of dark mass m_D with different Higgs mass m_h compared to 90% C.L. upper limits from DAMA, CoGeNT, CDMS and XENON. Future projected experimental sensitivities for superCDMS and Xenon100+ are also shown.

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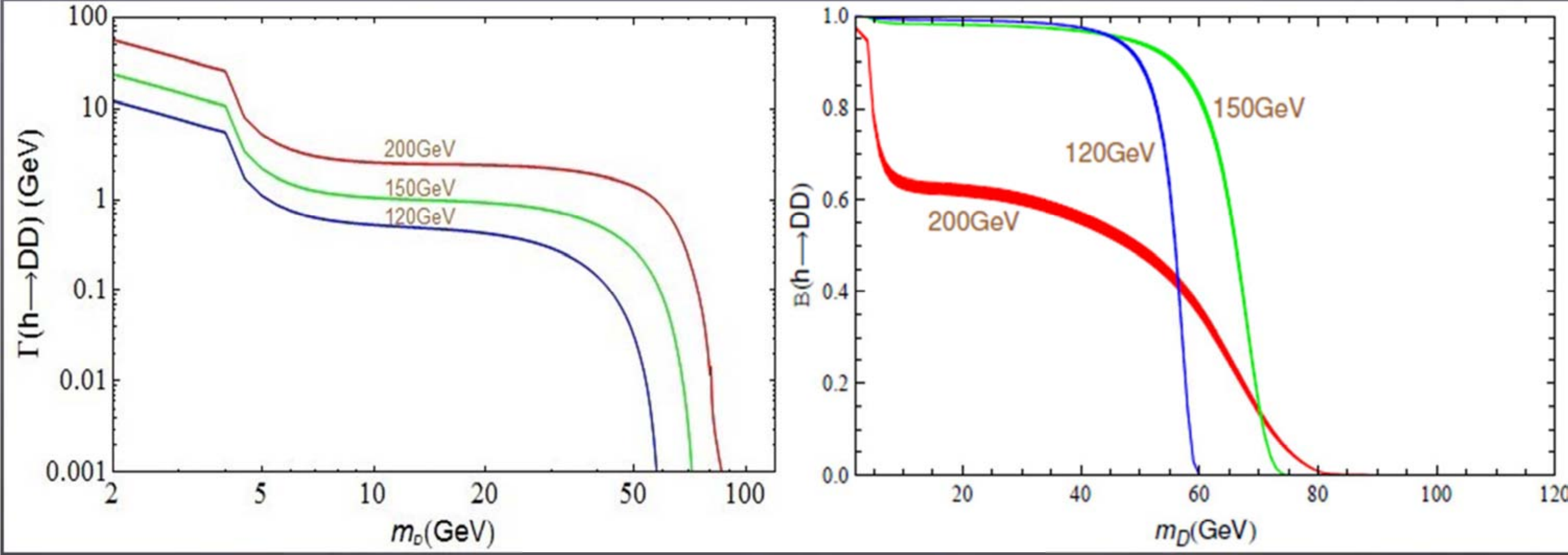
If Higgs mass is larger than 2 darkon mass, h can decay into darkon h -> DD, increasing invisible width.

$$\Gamma(h \to DD) = \frac{\lambda^2 v^2}{8\pi m_h^2}\sqrt{m_h^2 - 4m_D^2}$$



2. Two-Higgs-Doublet Model With A Darkon

The Yukawa interactions of the Higgs fields in the THDM II are given by

$$L_Y = -\bar{Q}_L \lambda_2^u \tilde{H}_2 U_R - \bar{Q}_L \lambda_1^d H_1 D_R - \bar{L}_L \lambda_1^l H_1 E_R + h.c.$$

where Q, U, D, L, and E represent the usual quark and lepton fields and $\lambda^{u,d,l}$ are Yukawa couplings. It is a discrete Z_2' symmetry, $H_2 \to -H_2$. In terms of their components, the Higgs doublets are

$$H_k = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} h_k^+ \\ \upsilon_k + h_k + i I_k \end{pmatrix}$$

where k=1,2 and υ_k is the VEV of H_k. Here h_k^+, I_k are related to the physical Higgs boson H^+, A and the Goldstone bosons w and z.

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$$\begin{pmatrix} h_1^+ \\ h_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} w^+ \\ H^+ \end{pmatrix} \quad \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

with $\tan\beta = {}^{v_2}\!/_{v_1}$, whereas h_k can be expressed in terms of mass eigenstates H and h as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

the angle α indicates the mixing of the two CP-even Higgs bosons.

Then, the THDM+D darkon Lagrangian

$$L_D = -\frac{\lambda_D}{4} D^4 - \frac{m_0^2}{2} D^2 - (\lambda_1 H_1^+ H_1 + \lambda_2 H_2^+ H_2) D^2$$

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After electroweak symmetry breaking, the darkon Lagrangian and the Yukawa interactions of h and H are described by

$$
\begin{aligned}
m_D^2 &= m_0^2 + \left(\lambda_1 \cos^2\beta + \lambda_2 \sin^2\beta\right) v^2 \,, \\
\mathcal{L}_{DDh} &= -\left(-\lambda_1 \sin\alpha \cos\beta + \lambda_2 \cos\alpha \sin\beta\right) v\, D^2\, h \;=\; -\lambda_h v\, D^2\, h \,, \\
\mathcal{L}_{DDH} &= -\left(\lambda_1 \cos\alpha \cos\beta + \lambda_2 \sin\alpha \sin\beta\right) v\, D^2\, H \;=\; -\lambda_H v\, D^2\, H \,,
\end{aligned}
$$

$$
L_{ffH} = -\bar{U}_L M^u U_R \left(\frac{\cos\alpha}{\sin\beta}\frac{H}{\upsilon} + \frac{\sin\alpha}{\sin\beta}\frac{h}{\upsilon} \right) - \bar{D}_L M^d D_R \left(-\frac{\sin\alpha}{\cos\beta}\frac{H}{\upsilon} + \frac{\cos\alpha}{\cos\beta}\frac{h}{\upsilon} \right)
$$

$$
-\bar{E}_L M^l E_R \left(-\frac{\sin\alpha}{\cos\beta}\frac{H}{\upsilon} + \frac{\cos\alpha}{\cos\beta}\frac{h}{\upsilon} \right) + h.c.
$$

The coupling between the CP-even Higgs bosons and the vector bosons

$$
L_{VVH} = \left(\frac{2m_W^2}{\upsilon} W^{+\mu} W_\mu^- + \frac{m_Z^2}{\upsilon} Z^\mu Z_\mu \right) \left(H \sin(\beta-\alpha) + h\cos(\beta-\alpha)\right)
$$

The annihilation ratio is given by,

$$\sigma_{ann}\upsilon_{rel}=\frac{8\lambda_h^2\upsilon^2}{(4m_D^2-m_h^2)^2+\Gamma_h^2m_h^2}\frac{\sum_i\Gamma(\tilde{h}\to X_i)}{2m_D}+\frac{8\lambda_H^2\upsilon^2}{(4m_D^2-m_H^2)^2+\Gamma_H^2m_H^2}\frac{\sum_i\Gamma(\tilde{H}\to X_i)}{2m_D}$$

where $\Gamma(\tilde{H}\to X_i)$ indicates the decay width of H into SM particles with a virtual mass of $2m_D$.

The cross section of the darkon-nucleon elastic scattering in the THDM+D as

$$\sigma_{el}\simeq\frac{\upsilon^2m_N^2}{\pi(m_D+m_N)^2}\left(\frac{\lambda_h g_h^{THDM}}{m_h^2}+\frac{\lambda_H g_H^{THDM}}{m_H^2}\right)^2$$

Based on chiral perturbation theory, the nucleon coupling to h or H is

$$g_{NN\mathcal{H}}^{\mathrm{THDM}} = (k_u^{\mathcal{H}} - k_d^{\mathcal{H}})\frac{\sigma_{\pi N}}{2v} + k_d^{\mathcal{H}}\frac{m_N}{v} + \frac{4k_u^{\mathcal{H}} - 25k_d^{\mathcal{H}}}{27}\frac{m_B}{v}$$

$$k_u^h = \frac{\sin\alpha}{\sin\beta}, \qquad k_d^h = \frac{\cos\alpha}{\cos\beta}, \qquad k_u^H = \frac{\cos\alpha}{\sin\beta}, \qquad k_d^H = -\frac{\sin\alpha}{\cos\beta}$$

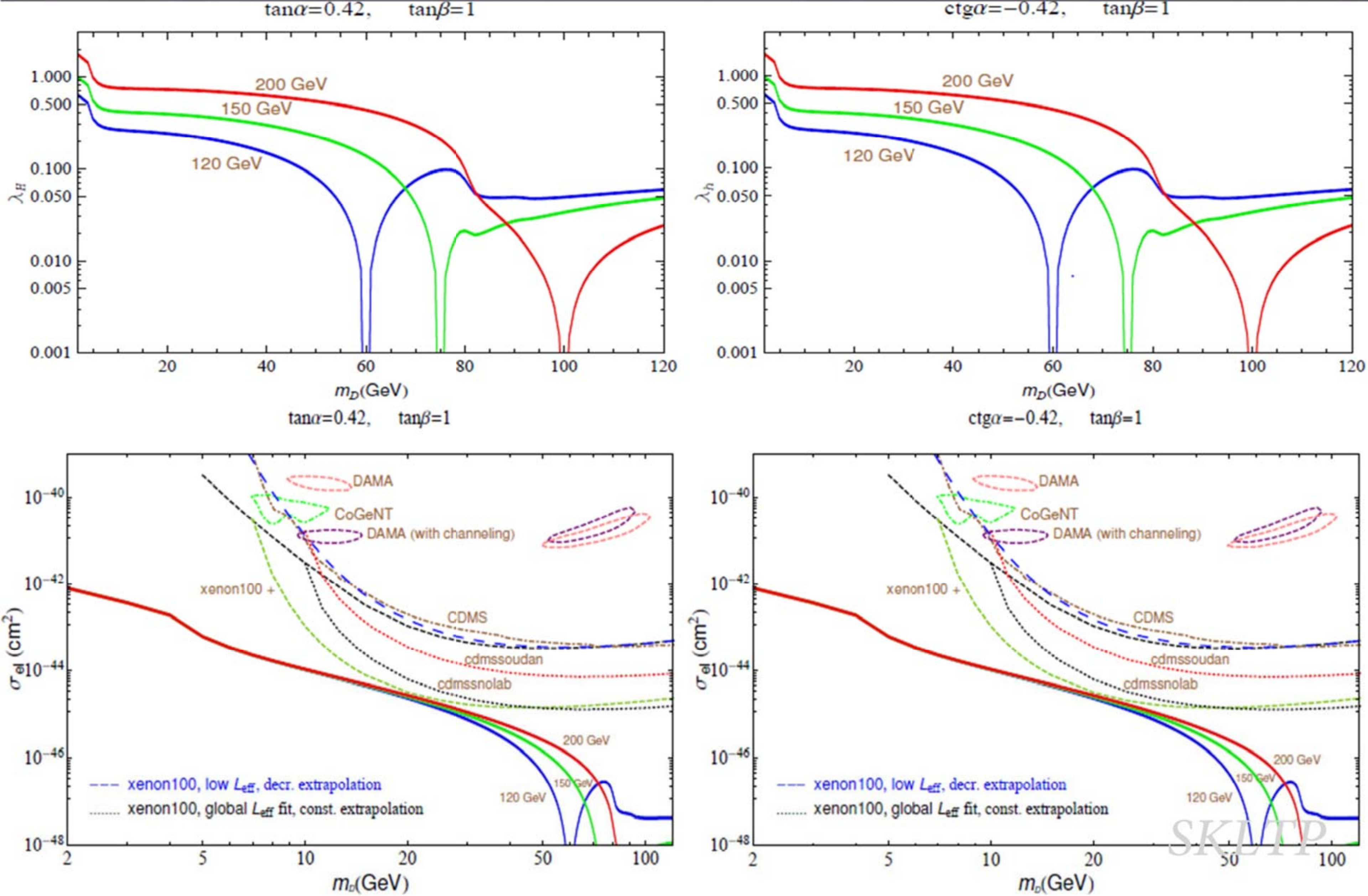
The cancellation condition is

$$\frac{k_d^{\mathcal{H}}}{k_u^{\mathcal{H}}} = \frac{27\,\sigma_{\pi N} + 8\,m_B}{27\,\sigma_{\pi N} + 50\,m_B - 54\,m_N} = -0.405$$

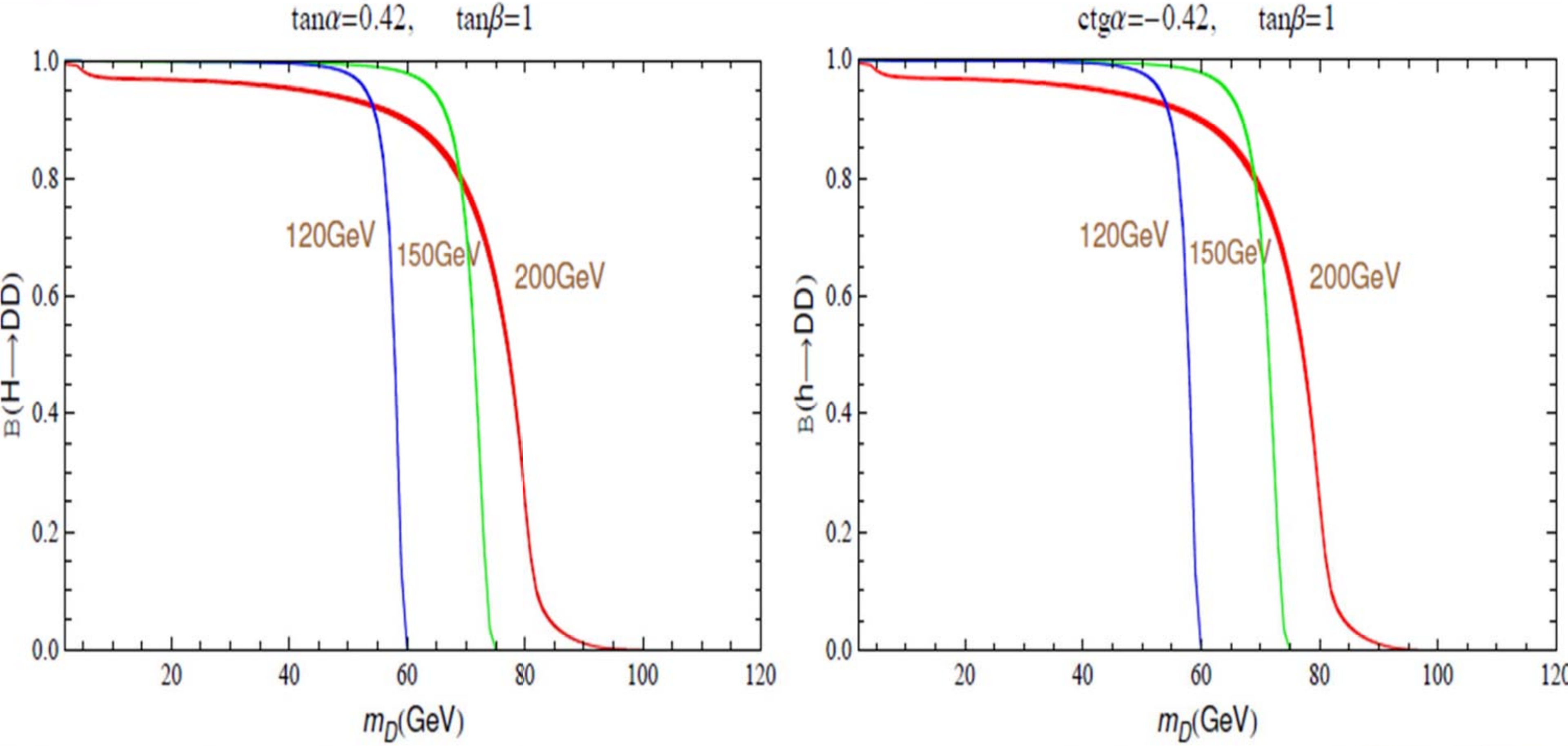
In the vicinity of -0.405, we select -0.42

$$k_d^H/k_u^H = -\tan\alpha\tan\beta = -0.42 \qquad k_d^h/k_u^h = \tan\beta/\tan\alpha = -0.42$$

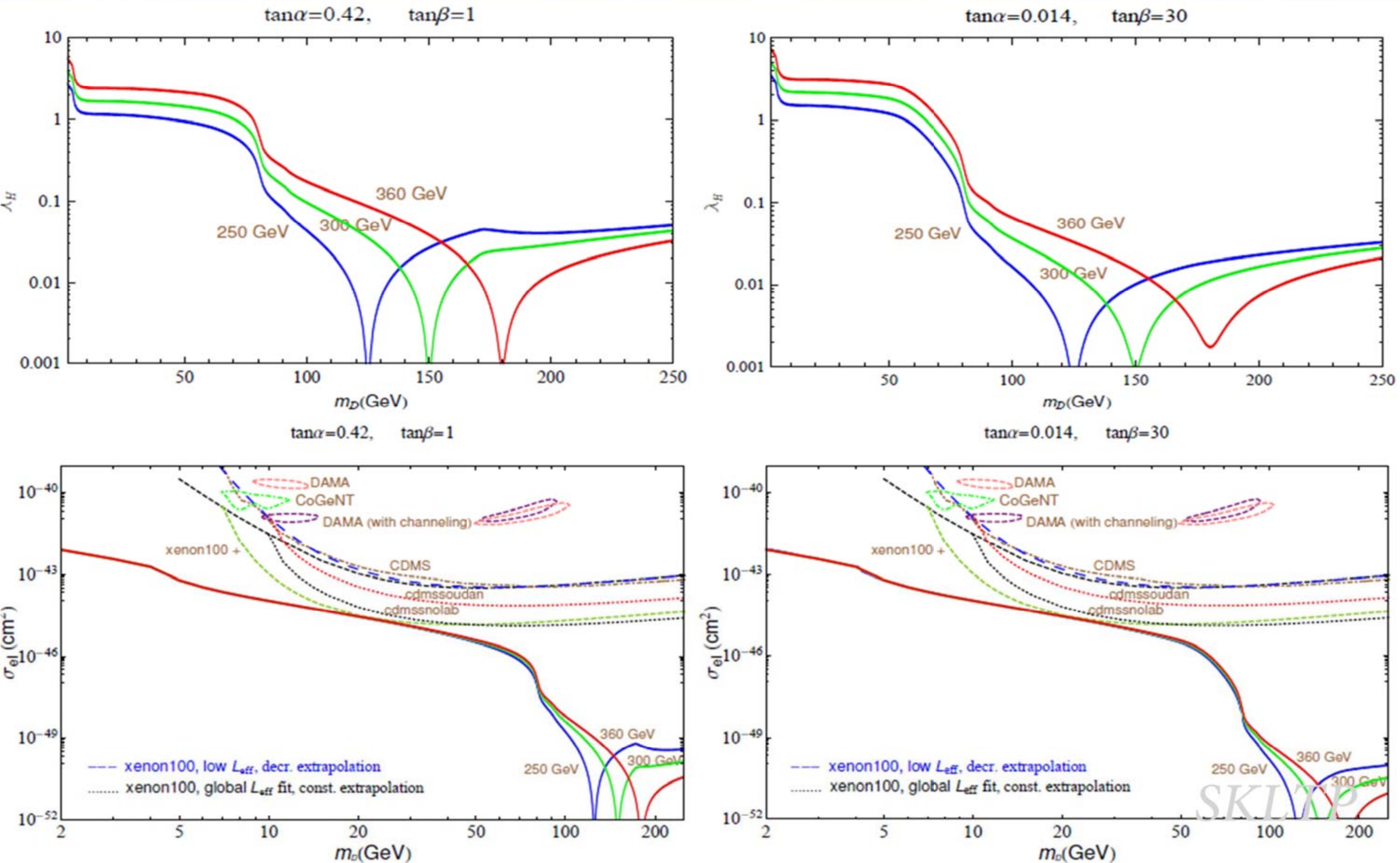
Only one lighter Higgs boson H or h responsible to DM physics.



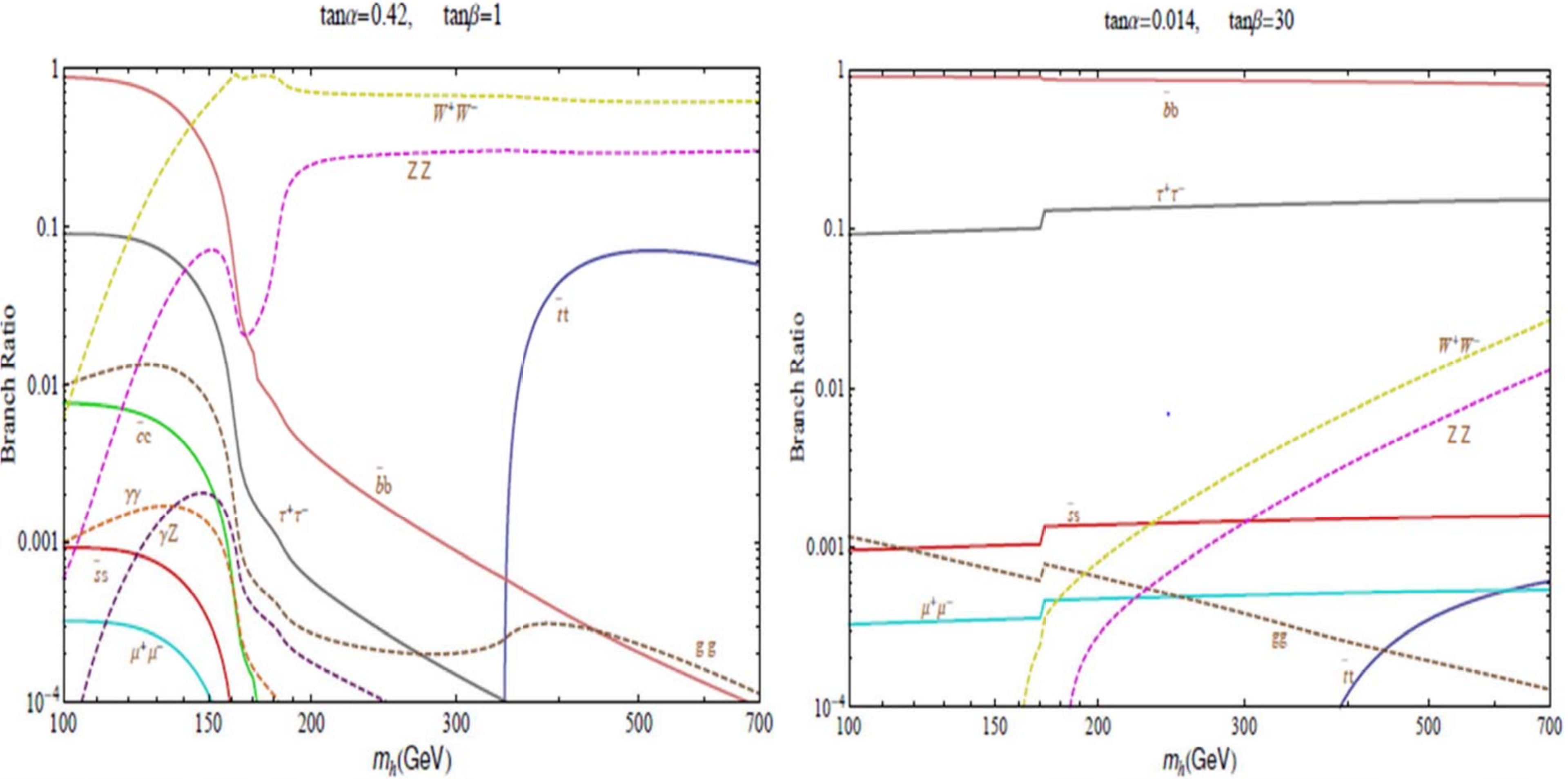
Branch ratio:



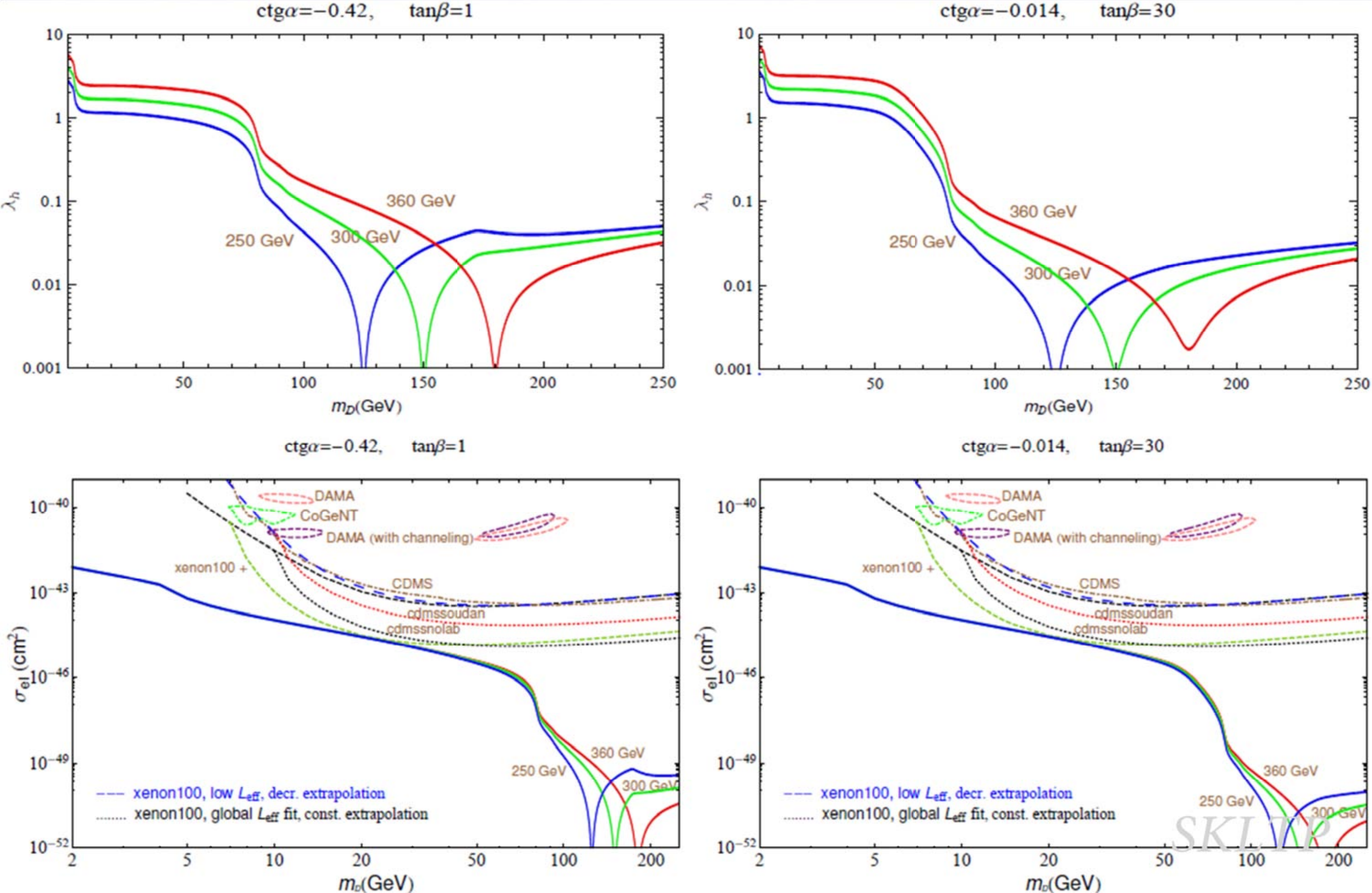
The lighter Higgs boson does not play a significant role in the DM physics, and the DM relic density is mainly determined by the interaction between the heavier Higgs and the darkon. For Higgs H,

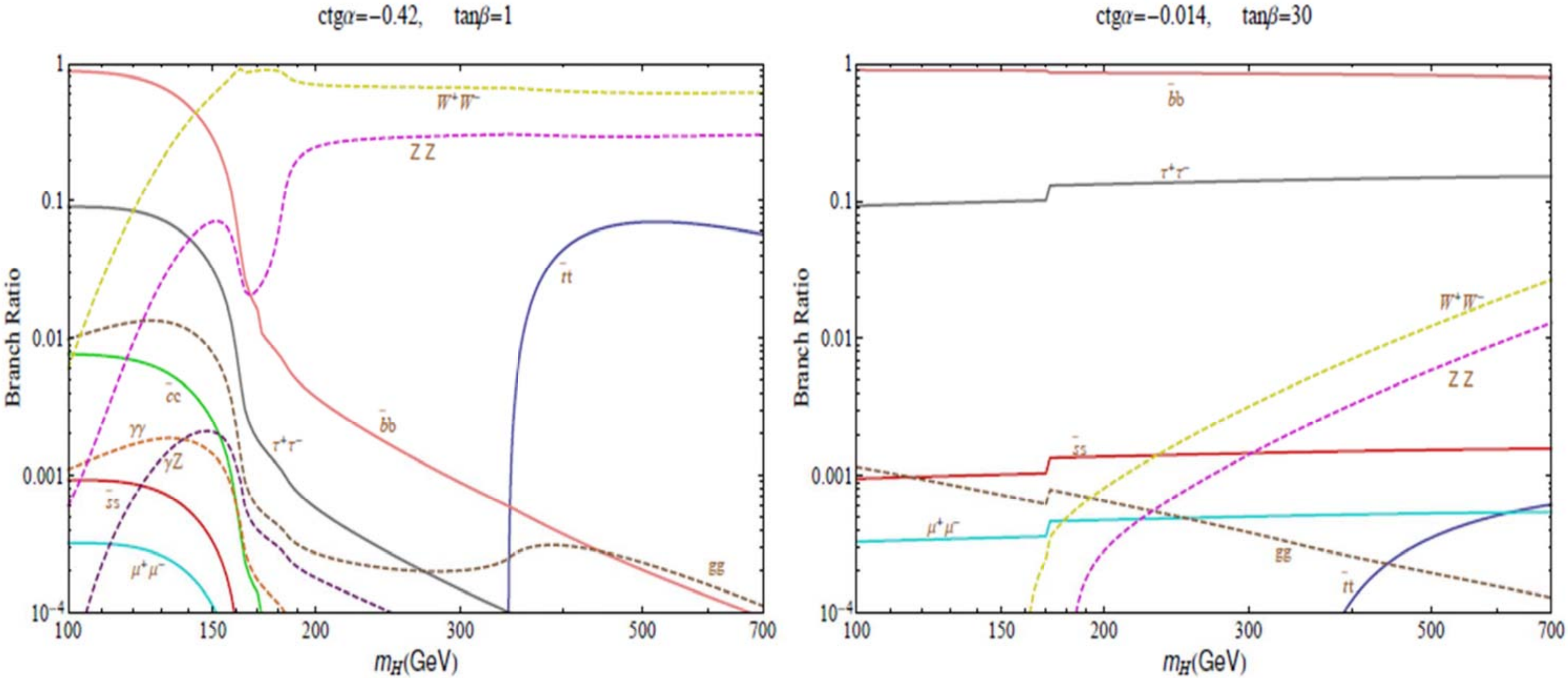


The lighter Higgs boson to be detected at the LHC with a small invisible branching ratio.



For Higgs boson h





The large tanbeta the branching ratios of Higgs to down-type fermion decay are largely enhanced due to large down-type Yukawa couplings. Comparing experimental data with theoretical predictions for branching ratios, information on mixing parameter of the two CP even Higgs boson can be obtained.

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3. Discussions and Conclusions

1. The Standard Model (SM) plus a real gauge-singlet scalar field dubbed darkon (SM+D) is the simplest model possessing a weakly interacting massive particle (WIMP) dark-matter candidate. In this model, the parameters are constrained from dark matter relic density and direct searches.

2. Then, We extend the SM+D to a two-Higgs-doublet model plus a darkon (THDM+D) it is possible to have a Higgs boson with a small invisible branching ratio and at the same time the dark matter can have a low mass.

Thank you!